

Star Formation & Stellar Evolution: Future Surveys & Instrumentation

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Abstract. The next generation of multi-object spectrographs (MOS) will deliver comprehensive surveys of the Galaxy, Magellanic Clouds and nearby dwarfs. These will provide us with the vast samples, spanning the full extent of the Hertzsprung–Russell diagram, that are needed to explore the chemistry, history and dynamics of their host systems. Further ahead, the Extremely Large Telescopes (ELTs) will have sufficient sensitivity and angular resolution to extend stellar spectroscopy well beyond the Local Group, opening-up studies of the chemical evolution of galaxies across a broad range of galaxy types and environments. In this contribution I briefly reflect on current and future studies of stellar populations, and introduce plans for the MOSAIC instrument for the European ELT.

1. Introduction

Considerable breakthroughs in studies of stellar populations have been enabled over the past 15 years by the development of high-multiplex optical spectrographs, such as AAT-2dF (Lewis et al. 2002), VLT-FLAMES (Pasquini et al. 2002), and Magellan-IMACS (Dressler et al. 2011). These powerful instruments have typically been used to compile large samples of stellar spectra to address questions in stellar evolution (e.g., Evans et al. 2005, 2011), or to use stars as tracers of the dynamics and assembly histories of galaxies (e.g., Zoccali et al. 2014).

This contribution highlights some of the plans for new multi-object spectrographs (MOS) in the coming decade, and some of the opportunities they will bring for studies of stellar populations. Sections 2 and 3 considers recent developments for 4-10 m class observatories, while Section 4 looks forward to future MOS observations with the European Extremely Large Telescope (E-ELT), which was recently approved for construction by ESO Council (de Zeeuw, Tamai & Liske, 2014).

2. Boldly into the near-IR with new technologies

One of the most exciting developments in the past couple of years has been the arrival of the first near-IR MOS instruments on large telescopes: Keck-MOSFIRE (McLean et al. 2012) and VLT-KMOS (Sharples et al. 2013). Although employing different technologies/approaches, i.e., a configurable cryogenic slit unit cf. deployable integral field units (IFUs), both are highly capable instruments for stellar studies, enabling efficient collection of relatively large spectroscopic samples in the near-IR for the first time.

2.1. Red supergiants as cosmic abundance probes

As an example of the new research enabled by access to near-IR MOS observations, I highlight recent studies of the physical properties and chemical abundances of red supergiants (RSGs), the cool, luminous descendants of massive stars. The potential of *J*-band spectroscopy of RSGs to determine chemical abundances in galaxies was introduced by Davies, Kudritzki & Figer (2010) in their analysis of archival spectra from the IRTF library (Rayner, Cushing & Vacca, 2009). The spectral window used in this approach is shown in Fig. 1, and has been further validated by studies of RSGs in the Galaxy (Gazak et al. 2014) and in the Magellanic Clouds (Davies et al. 2015).

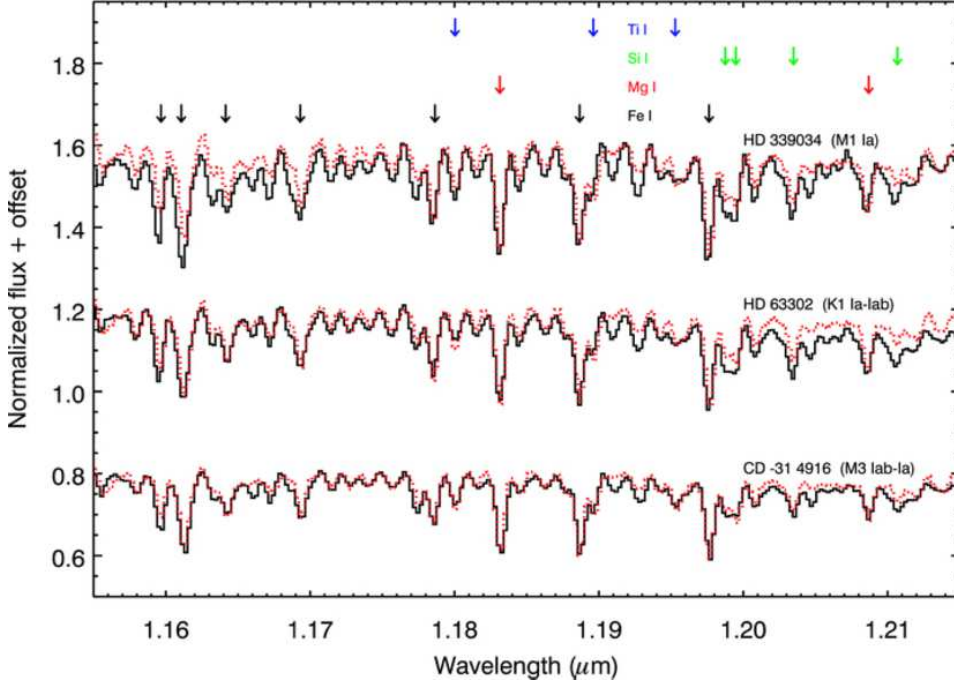


Figure 1. Illustrative fits (dotted lines) to *J*-band spectra of RSGs from Davies, Kudritzki & Figer (2010). This region is relatively free of telluric and sky-emission lines and contains useful diagnostic atomic features.

A first application of this technique at larger distances was demonstrated by KMOS Science Verification observations of eleven RSGs in NGC 6822 ($d = 0.46$ Mpc), with an estimated mean metallicity, $[Z]$, of -0.52 ± 0.21 (Patrick et al. 2015). The final test phase of this technique was KMOS Guaranteed Time Observations in NGC 300 ($d \sim 1.9$ Mpc), enabling a comparison of the RSG abundances (Gazak et al. 2015, see Fig. 2) with those for blue supergiants from Kudritzki et al. (2008). With the method now tested rigorously in the local Universe, efforts are underway to observe a larger sample of galaxies (spanning a range of masses) to obtain a direct calibration of the mass-metallicity relation (see, e.g., Kewley & Ellison, 2008).

In addition to observational factors such as sky and telluric subtraction, quantitative stellar work in the near-IR also presents new challenges in the sense that much of the focus on atomic data has traditionally been at optical wavelengths, so new calculations are required to, for instance, account for deviations from the approximation

of local thermodynamic equilibrium (Bergemann et al. 2012; 2013; 2015). Continued efforts will be required in this area if we are to obtain the maximum benefit from future facilities, both from the 8-10 m class telescopes and the ELTs.

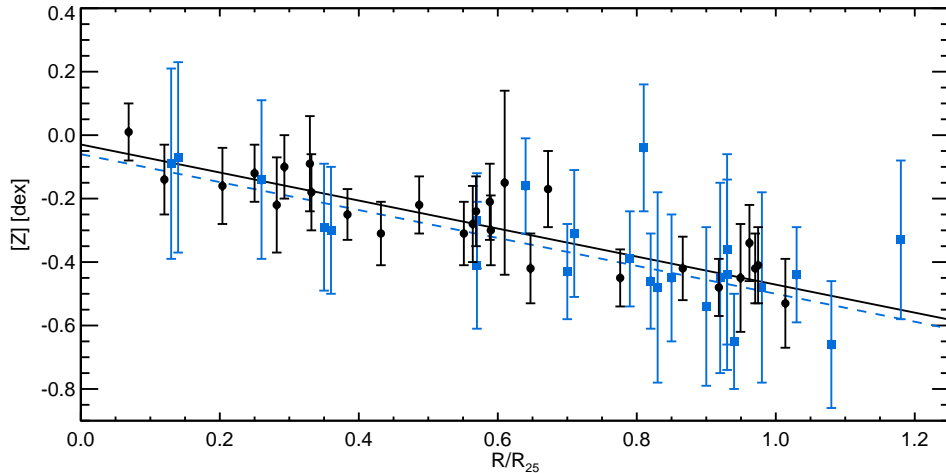


Figure 2. Stellar metallicities and gradients in NGC 300 (Gazak et al. 2015). The results from optical spectroscopy of blue supergiants (Kudritzki et al. 2008, shown in blue) and the near-IR observations of RSGs (in black) are in excellent agreement.

3. Spectroscopy of stellar populations in 2020

Beyond the facilities already in operation on ground-based telescopes, there are four MOS projects in the design/construction phase that each have ‘legacy’-style large surveys of stellar populations as part of their core programmes:

- 4MOST: Optical MOS for the 4 m VISTA telescope (de Jong, this vol.);
- MOONS: (red-)optical/near-IR MOS for the VLT (Cirasuolo, this vol.);
- PFS: Optical/near-IR MOS for the Subaru Telescope (Takada, this vol.);
- WEAVE: Optical MOS for the WHT (Dalton, this vol.).

The surveys enabled by this next generation of instruments will provide a truly vast ($>10^6$ stars) census of the stellar populations of the inner Milky Way, its disk and halo populations, the Magellanic Clouds, and the dwarf/irregular galaxies of the Local Group. Other instruments under construction such as GTC-MEGARA (de Paz, this vol.) and GTC-EMIR (Garzon, this vol.) will also contribute valuable observations.

Many of the detailed plans for the stellar surveys with these new instruments are presented elsewhere in this volume. As an example of studies of star formation (specifically whether it always occurs in dense clusters), spatial analyses of star-forming regions can already provide us with insights into their initial conditions and dynamical evolution (e.g., Parker et al. 2014; Wright et al. 2014), but the information encoded in the radial velocities (from the spectroscopy) and proper motions (from the *Gaia* mission) will give us unique three-dimensional information to trace their dynamical histories (e.g., to identify comoving groups with the different spatial sub-structures).

4. The Science Case for an ELT-MOS

*‘There’s a capacity for appetite that a whole heaven and earth of cake can’t satisfy’
John Steinbeck (East of Eden)*

The MOS facilities planned for the coming years will be transformative due to the combination of their large multiplexes with substantial telescope allocations to acquire the vast samples required. However, as we look further ahead, we are ultimately limited by the collecting area of current facilities. For instance, Keck-DEIMOS spectroscopy of the evolved stellar populations in M31 gives insufficient signal-to-noise below the tip of the red giant branch (at $I > 21.5$ mag, e.g., Chapman et al. 2006), and quantitative analysis of massive O-type stars is limited to all but the most luminous objects beyond 1 Mpc (e.g., Trammer et al. 2011, 2014).

The ELTs will provide a huge leap forward in both sensitivity and, via adaptive optics (AO), spatial resolution. In addition to ESO’s planned 39 m E-ELT, there are two other ELT projects now entering the construction phase: the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT). Some of the challenges of simply scaling-up current MOS designs and capabilities to ELT-class instruments are discussed by Bernstein (this vol.). Nonetheless, there is a huge range of scientific topics which require ELT-MOS observations, ranging from spectroscopic characterisation of the most distant galaxies, through to studies of exoplanets in stellar clusters (Evans et al. 2015).

4.1. MOSAIC: The MOS for the E-ELT

Following Phase A studies of three potential E-ELT MOS concepts (see Ramsay et al. 2010), European and Brazilian astronomers have combined their efforts to assemble a comprehensive science case for an ELT-MOS (Evans et al. 2015), working together on the MOSAIC instrument concept (Hammer et al. 2014).

The range of cases presented by Evans et al. (2015) flow down to instrument requirements which are knowingly broad (see their Table 7). This step was intended as a first census of all the potential cases and relevant parameter space for MOS observations. The Phase A conceptual design of MOSAIC is anticipated to start in late 2015, including scientific trade-offs of capability vs. cost (and technical feasibility). One of the key approaches in plans for MOSAIC has been the delineation of possible MOS sources into two types of observations, identified by Evans et al. (2012) as:

- *High definition:* Observations of tens of channels at fine spatial resolution, with multi-object adaptive optics (MOAO) providing high-performance correction for selected sub-fields.
- *High multiplex:* Integrated-light (or coarsely-resolved) observations of >100 objects at the spatial resolution given by the ground-layer adaptive optics (GLAO) of the telescope.

The technical readiness of the high-definition mode has advanced significantly over the past few years thanks to the CANARY project on the WHT in La Palma. This has performed the first on-sky demonstrations of MOAO using natural guide stars (Gendron et al. 2011; Vidal et al. 2014) and, more recently, using laser guide stars. As illustrated by the point-spread functions in Fig. 3, while MOAO does not yield the same performance as single-conjugate AO, it is substantially better than that from seeing or

GLAO. The attraction of this approach is that such performance can potentially be obtained for multiple sub-fields within the large ($\sim 10'$ diameter) field of the E-ELT.

A second MOAO pathfinder, RAVEN on the Subaru Telescope, has also made impressive progress with on-sky tests in the past year (Lardi re et al. 2014). As an aside, note that even in the deep cosmological fields that are deliberately free of bright foreground stars, there are still sufficient (fainter) stars for significant improvements in image quality from MOAO (Basden, Evans & Morris, 2014).

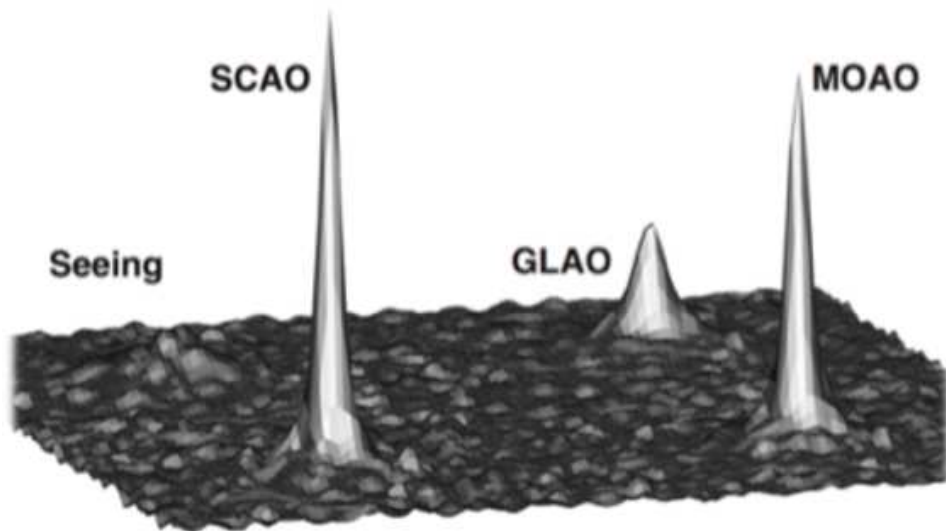


Figure 3. Example H -band point-spread functions from the CANARY experiment (Vidal et al. 2014), obtained without AO correction (seeing) and with ground-layer, multi-object, and single-conjugate AO (GLAO, MOAO, and SCAO, respectively).

4.2. Resolved stellar populations beyond the Local Group

A key component of the MOSAIC case, indeed for the ELTs in general, is concerned with stellar populations, both in the inner Milky Way and in distant systems beyond 1 Mpc. For example, when combined with AO, the J -band method introduced in Section 2.1 is potentially very powerful, opening-up direct abundance studies of RSGs out to distances of tens of Mpc (Evans et al. 2011). Work is now underway to explore this technique for lower-mass, evolved stars on the red giant branch, to compare it with the use of the Calcium triplet in estimation of stellar metallicities and radial velocities (e.g. Tolstoy et al. 2001; Battaglia et al. 2008).

An expanded case for this topic was presented by Evans et al. (2015). In short, MOSAIC spectroscopy will open-up studies of the evolved populations in galaxies such as the spirals in the Sculptor Group for the first time. If employing *high definition* AO-corrected observations with IFUs, note that the effective multiplex of stars observed in dense regions is likely to be much larger than simply the number of IFUs, potentially giving samples of 1000s of stars within a relatively modest amount of time. Equally, *high multiplex* optical spectroscopy would provide high-quality observations of massive

O-type stars to investigate their physical properties in galaxies beyond 1 Mpc and/or studies of the evolved stars in the interesting halo regions of these distant systems.

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